Formation
of dwarf spheroidal galaxies via tidal stirring and mergers

Ewa L. Łokas

Copernicus Center, Warsaw

Outline

- Introduction: the Local Group and its members
- The tidal stirring model: comparison between its predictions and observations
- How to make an ultra-faint dSph galaxy
- Mergers as another channel for the formation of dSph galaxies
- Summary

Collaborators

- Stelios Kazantzidis (Ohio State)
- Steven Majewski (Virginia)
- Lucio Mayer (Zurich)
- Alexander Knebe (Madrid)
- Jarosław Klimentowski (Warsaw)

dIrr versus dSph galaxies

NGC 6822

Leo I

dIrr

irregular/disky

rotating

contain gas

forming stars

dSph

elliptical

non-rotating

do not contain gas

not forming stars

Morphology-density relation: dSph galaxies are found closer to the big galaxies, while dIrrs occupy isolated regions at the outskirts of the LG

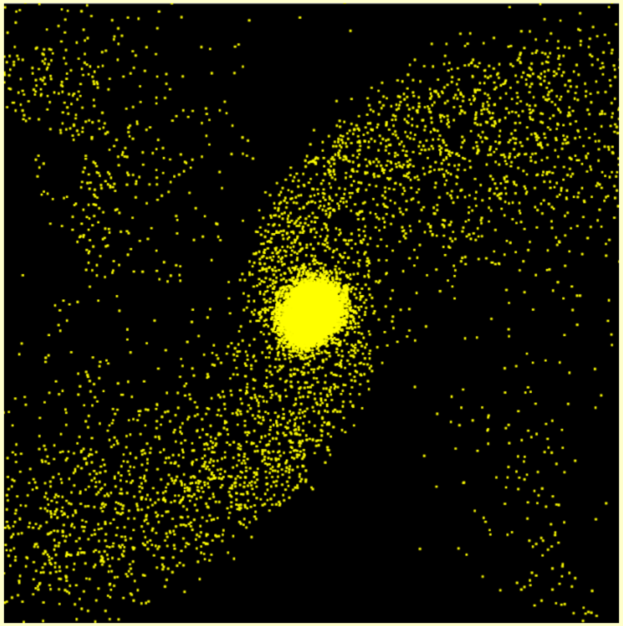
Tidal stirring scenario

- All dwarf galaxies were initially disks embedded in dark matter haloes
- In the vicinity of a big galaxy they are strongly affected by tidal forces
- Tidal forces cause strong mass loss and the formation of tidal tails
- The evolution involves morphological transformation, from a disk to a bar and then a spheroid
- Streaming motions of stars change to random motions

Mayer et al. 2001

Examples of simulations

- The simulations traced the evolution of a two-component dwarf galaxy on an eccentric orbit around the Milky Way for 10 Gyrs
- The dwarf initially had a stellar disk and an NFW-like dark matter halo
- The dwarf was modelled with 1.2×10^6 stellar and 10^6 dark matter particles
- The progenitor had an initial mass of $10^9\ M_\odot$



20 kpc

Klimentowski et al. 2007

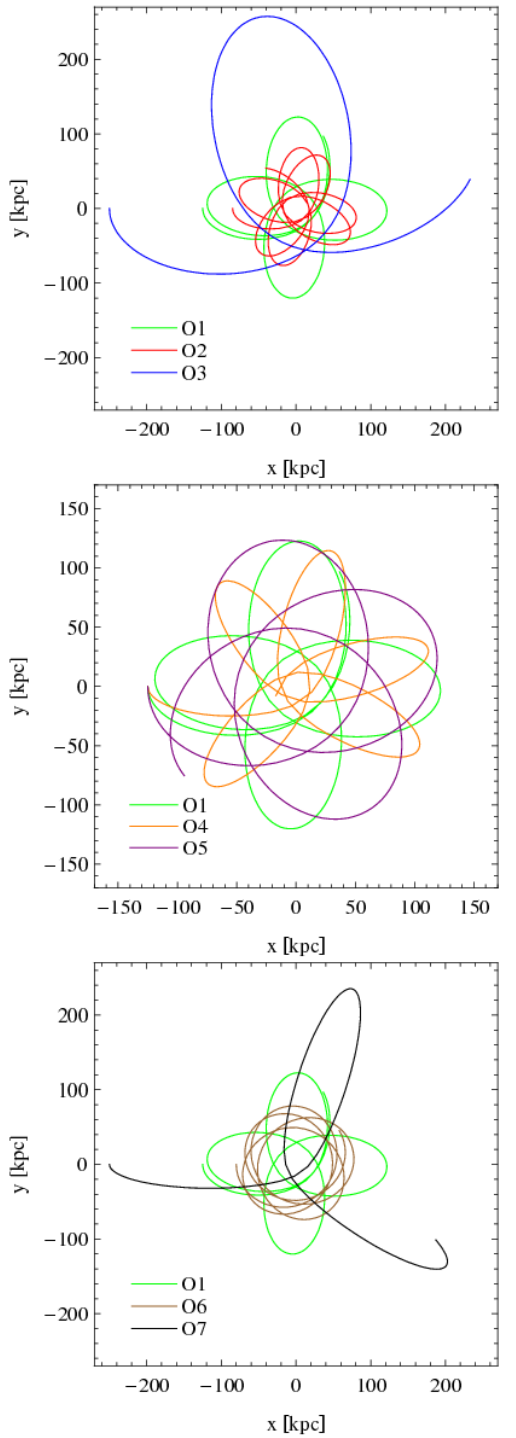
Kazantzidis et al. 2011

All simulations

Properties of the simulated dwarfs.

Simulation	Varied parameter	r_{apo} [kpc]	r_{peri} [kpc]	T_{orb} [Gyr]	t_{la} [Gyr]	r_{lim} [kpc]	M_V [mag]	$r_{1/2}$ [kpc]	μ_V [mag arcsec^{-2}]	V/σ	$e = 1 - b/a$	Color
O1	orbit	125	25	2.09	8.35	6.28	−11.7	0.36	23.4	0.36	0.20	green
O2	orbit	87	17	1.28	8.95	6.28	−10.2	0.33	24.6	0.08	0.03	red
O3	orbit	250	50	5.40	5.40	6.28	−12.8	0.44	22.5	1.30	0.66	blue
O4	orbit	125	12.5	1.81	9.05	6.28	−10.4	0.60	24.7	0.50	0.05	orange
O5	orbit	125	50	2.50	10.00	6.28	−12.3	0.41	22.9	0.81	0.55	purple
O6	orbit	80	50	1.70	8.50	6.28	−12.3	0.47	23.3	0.37	0.35	brown
O7	orbit	250	12.5	4.55	9.10	6.28	−11.8	0.46	23.6	0.62	0.39	black
S6	$i(-45°)$	125	25	2.09	8.35	6.28	−11.8	0.30	22.7	0.18	0.20	green
S7	$i(+45°)$	125	25	2.09	8.35	6.28	−12.0	0.45	23.3	0.25	0.26	red
S8	$z_d/R_d(-0.1)$	125	25	2.09	8.35	6.28	−11.8	0.34	23.2	0.62	0.27	blue
S9	$z_d/R_d(+0.1)$	125	25	2.09	8.35	6.28	−11.7	0.38	23.7	0.55	0.17	orange
S10	$m_d(-0.01)$	125	25	2.09	8.35	6.28	−10.9	0.38	24.5	0.45	0.09	purple
S11	$m_d(+0.02)$	125	25	2.09	8.35	6.28	−12.8	0.37	22.4	0.71	0.42	magenta
S12	$\lambda(-0.016)$	125	25	2.09	8.35	3.78	−12.3	0.22	21.8	0.64	0.25	cyan
S13	$\lambda(+0.026)$	125	25	2.09	8.35	6.94	−11.1	0.50	24.8	0.26	0.12	pink
S14	$c(-10)$	125	25	2.10	8.40	6.28	−11.4	0.35	23.7	0.31	0.14	black
S15	$c(+20)$	125	25	2.08	8.30	6.28	−12.2	0.37	23.2	0.96	0.32	gray
S16	$M_h(\times 0.2)$	125	25	2.14	8.55	3.67	−10.1	0.25	24.4	0.37	0.17	brown
S17	$M_h(\times 5)$	125	25	1.88	9.40	7.00	−13.1	0.48	22.8	0.63	0.18	yellow

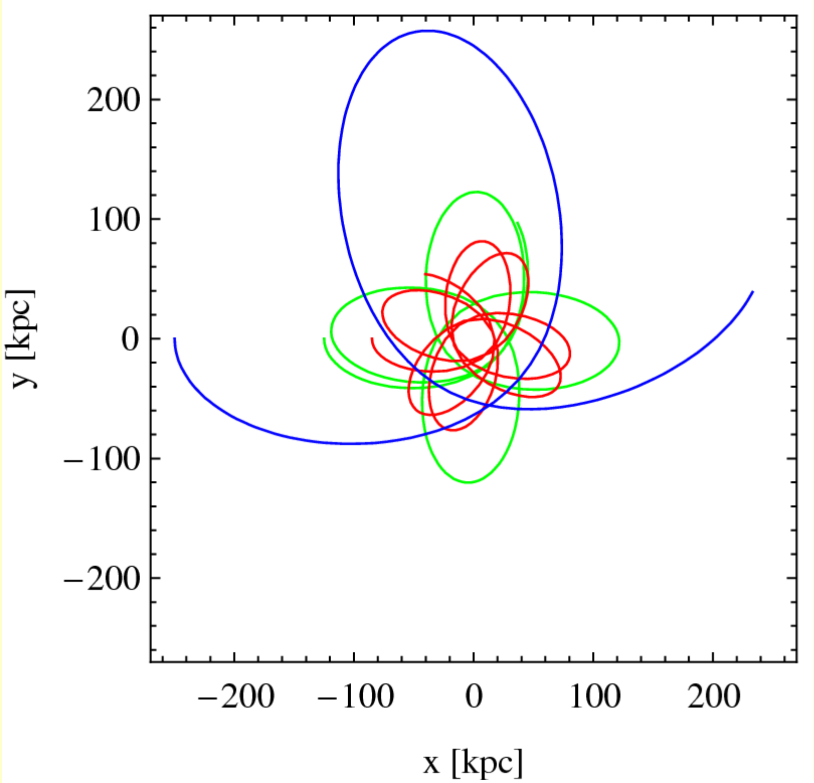
Orbits



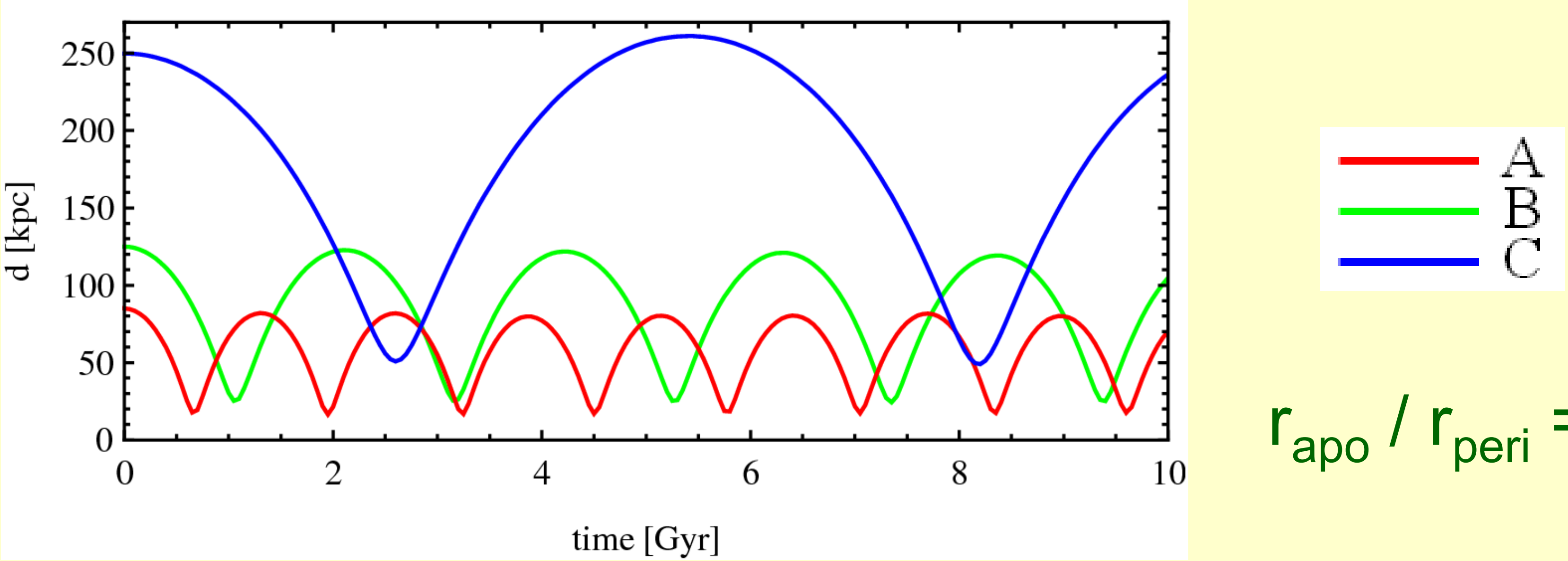
Orbits of different size and eccentricity:

Simulation	Varied parameter	r_{apo} [kpc]	r_{peri} [kpc]	T_{orb} [Gyr]
O1	orbit	125	25	2.09
O2	orbit	87	17	1.28
O3	orbit	250	50	5.40
O4	orbit	125	12.5	1.81
O5	orbit	125	50	2.50
O6	orbit	80	50	1.70
O7	orbit	250	12.5	4.55

Three simulated cases

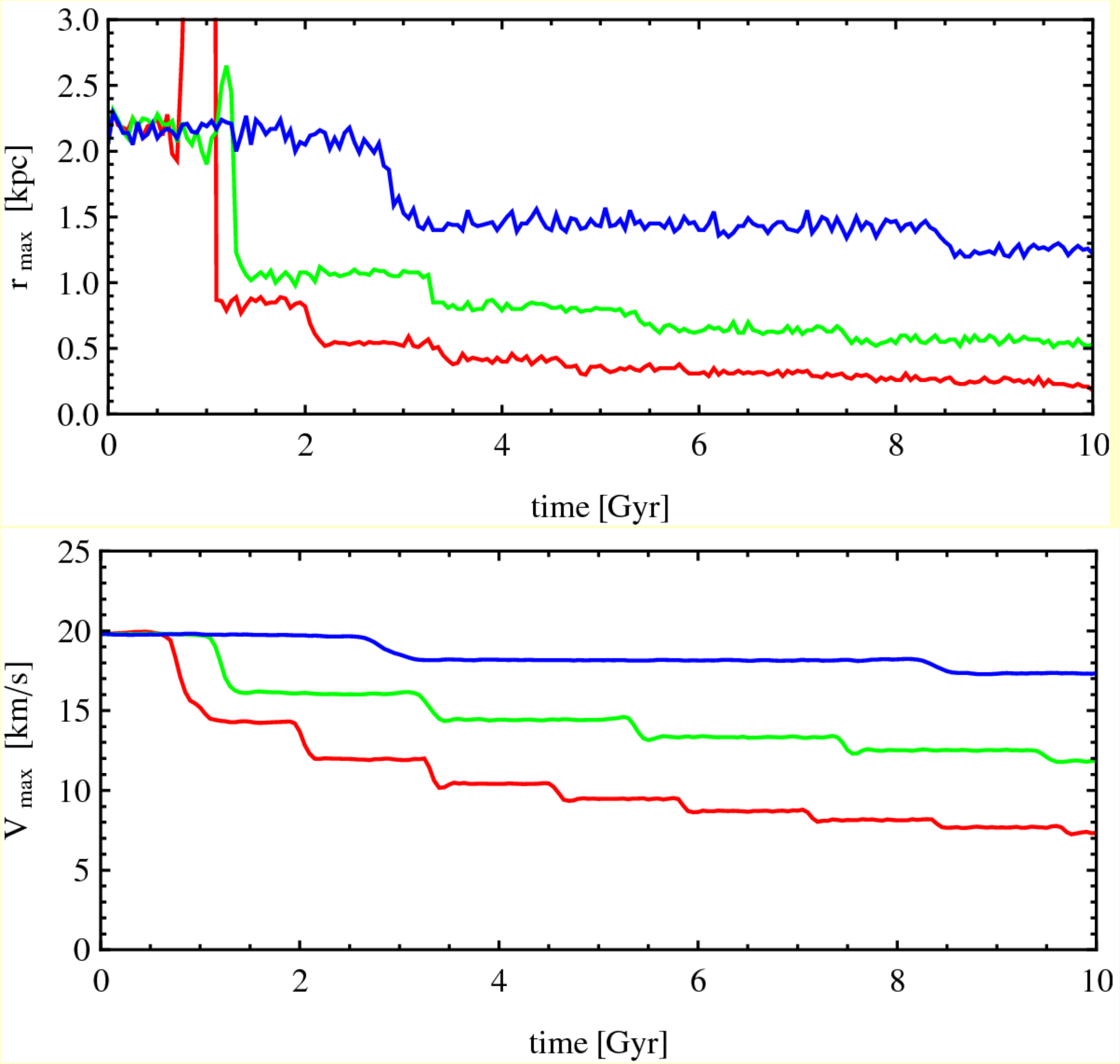


Three orbits of different size, other parameters unchanged

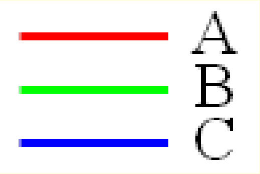


$r_{apo} / r_{peri} = 5$

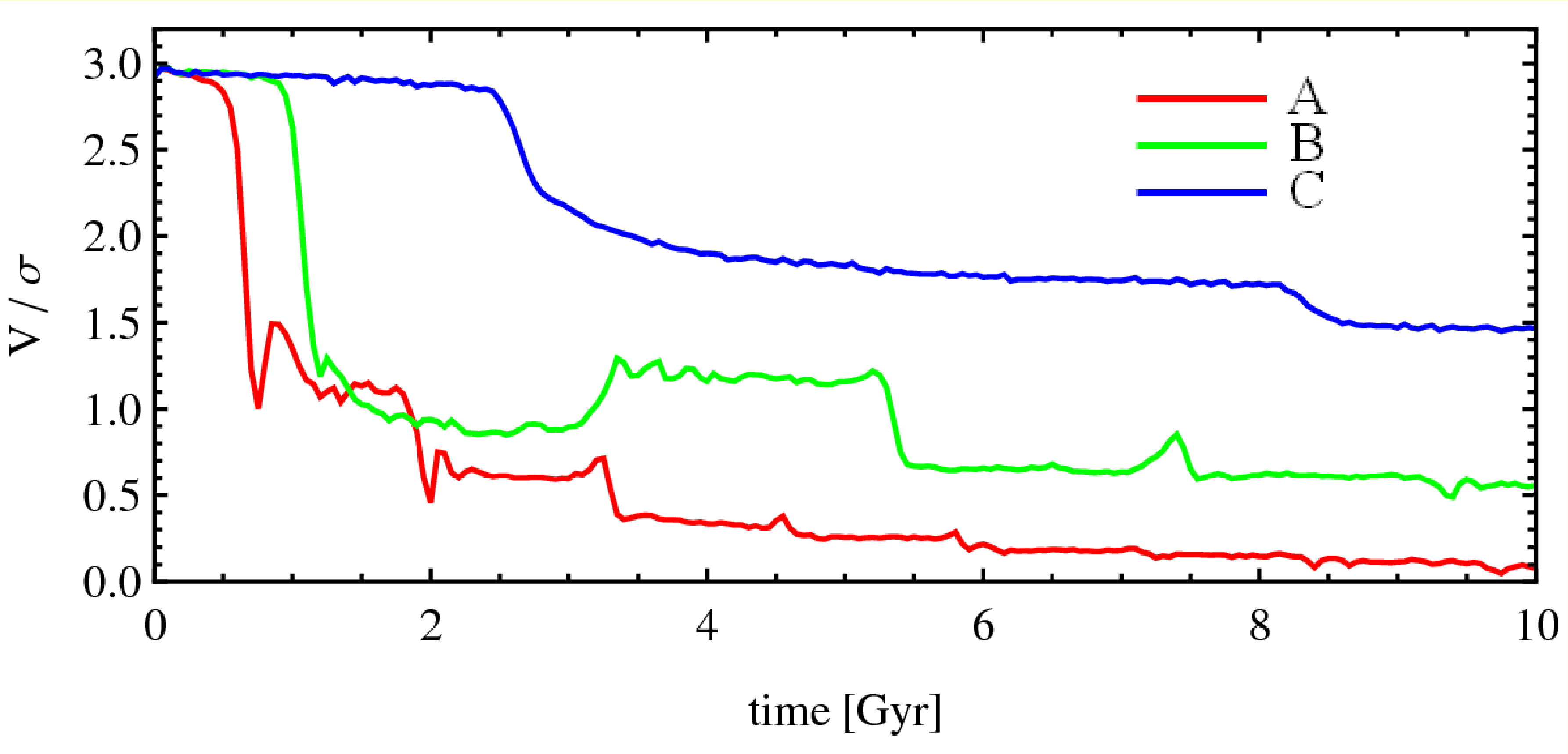
Mass and size evolution



- r_{max} is a characteristic radius where V_{circ} has a maximum
- V_{max} is a good measure of the mass



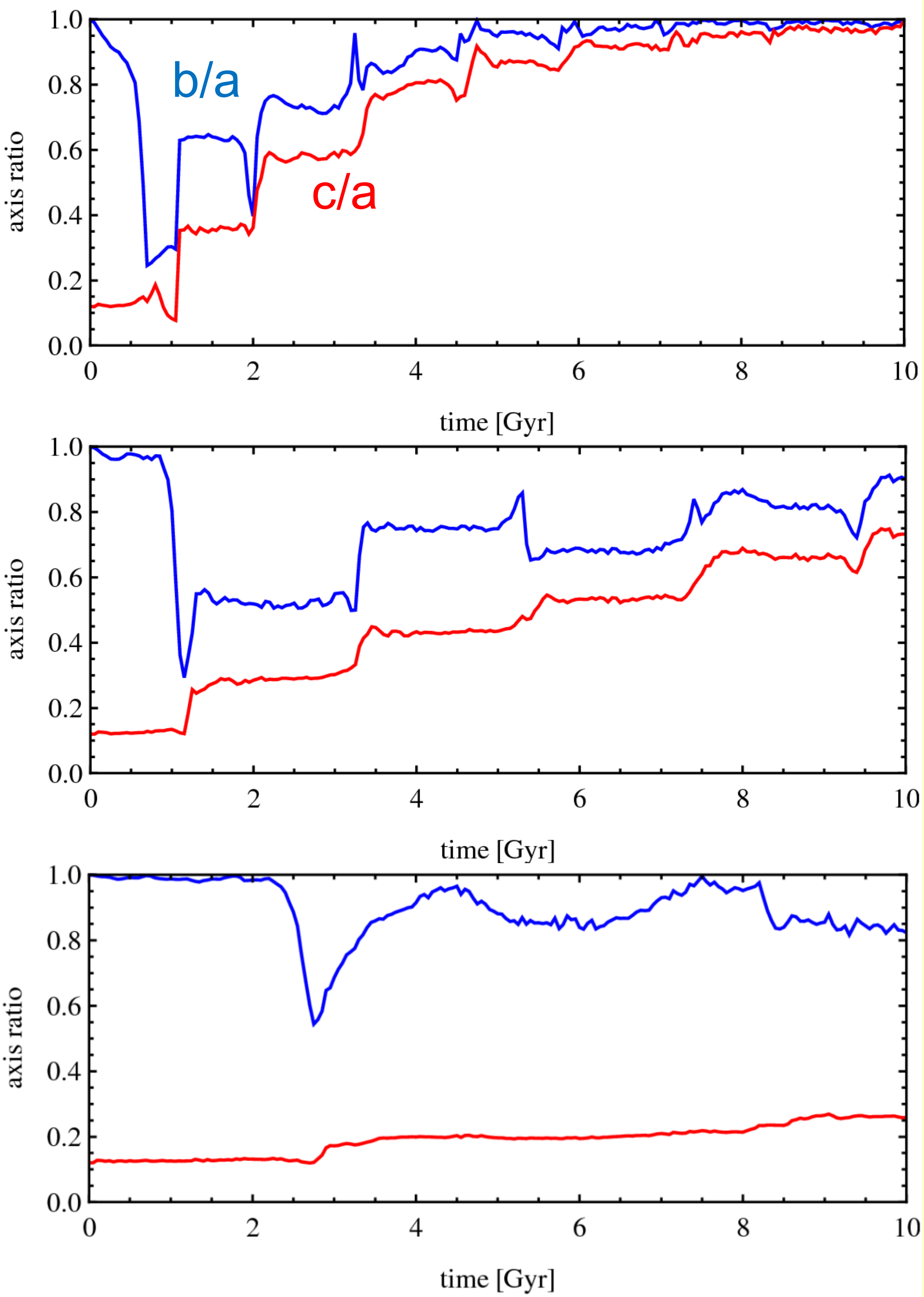
Streaming to random motion



$V = V_\phi$ – rotation around the shortest axis

$\sigma = [(\sigma_r^2 + \sigma_\vartheta^2 + \sigma_\phi^2)/3]^{1/2}$ – 1D velocity dispersion

Axis ratios



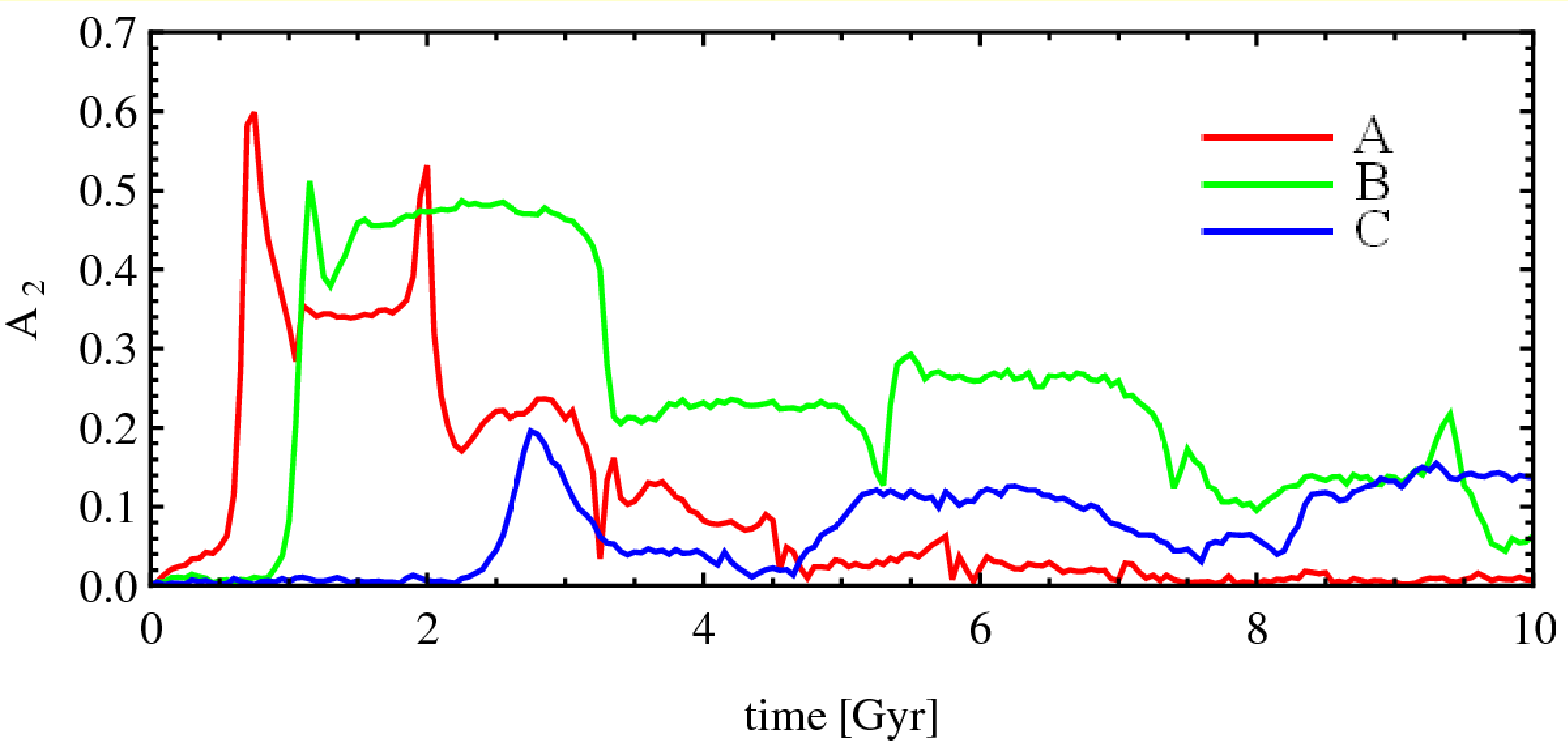
A

B

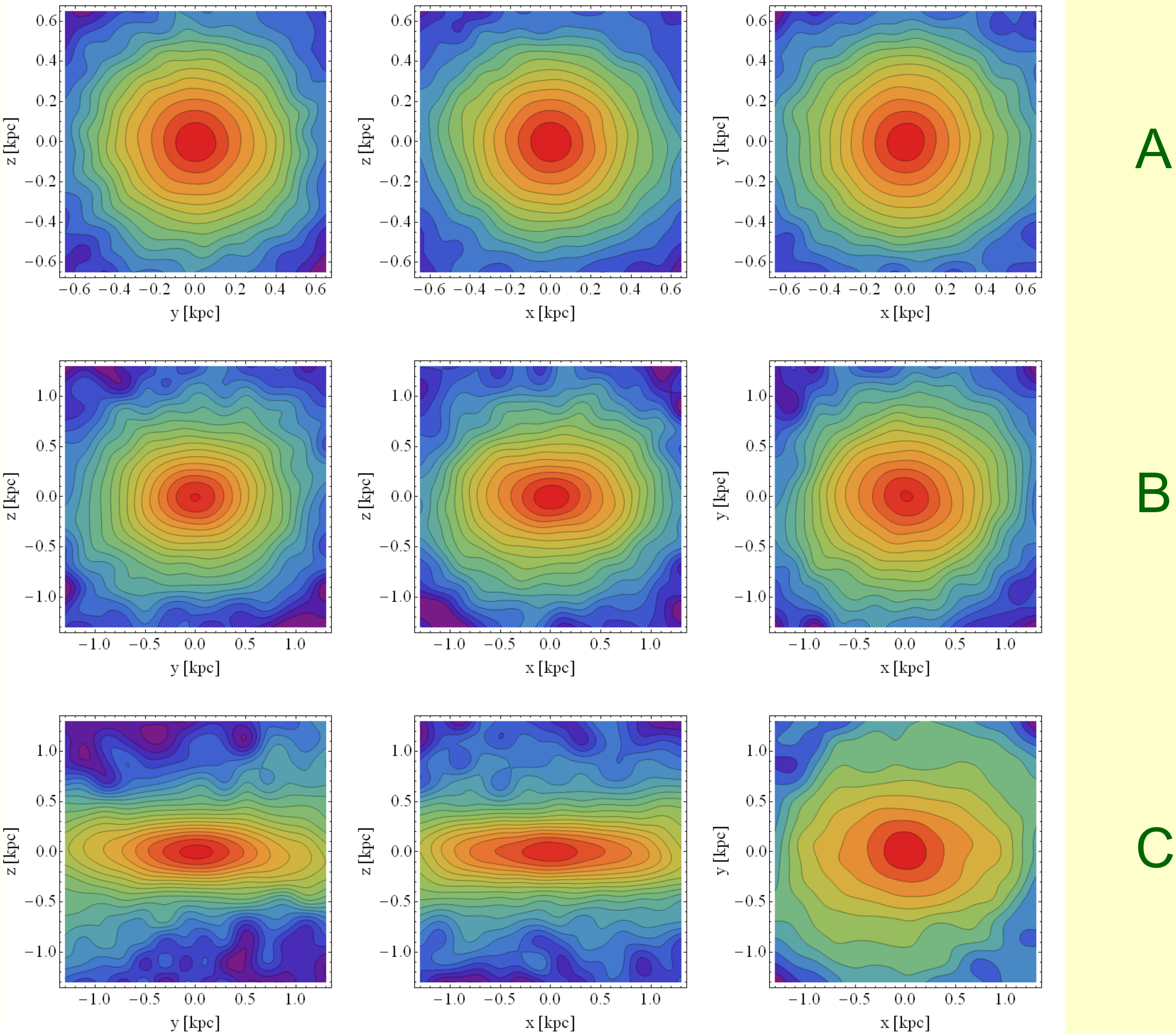
C

- Model A ends up spherical
- Model B is triaxial
- Model C remains disky

Morphological evolution



- The disk transforms into a bar which becomes more spherical with time
- The distribution of stars is in general not spherical



y [kpc]
x [kpc]
z [kpc]
y [kpc]
A
B
C

Observational parameters

Properties of the dwarfs as measured by an observer positioned at the center of the Milky Way:

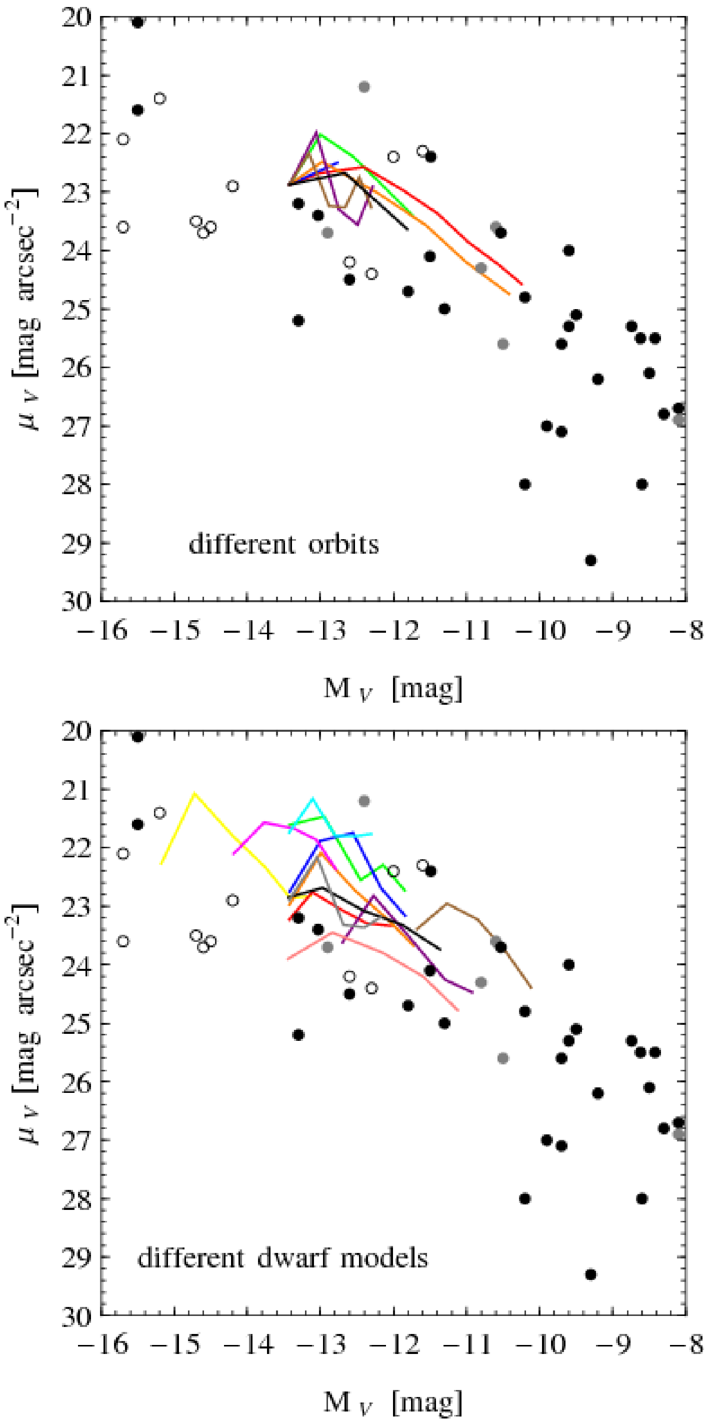
M_V – the total visual magnitude

$r_{1/2}$ – the half-light radius

μ_V – the central surface brightness

V/σ – the ratio of rotation velocity to central velocity dispersion

$e=1-b/a$ - ellipticity

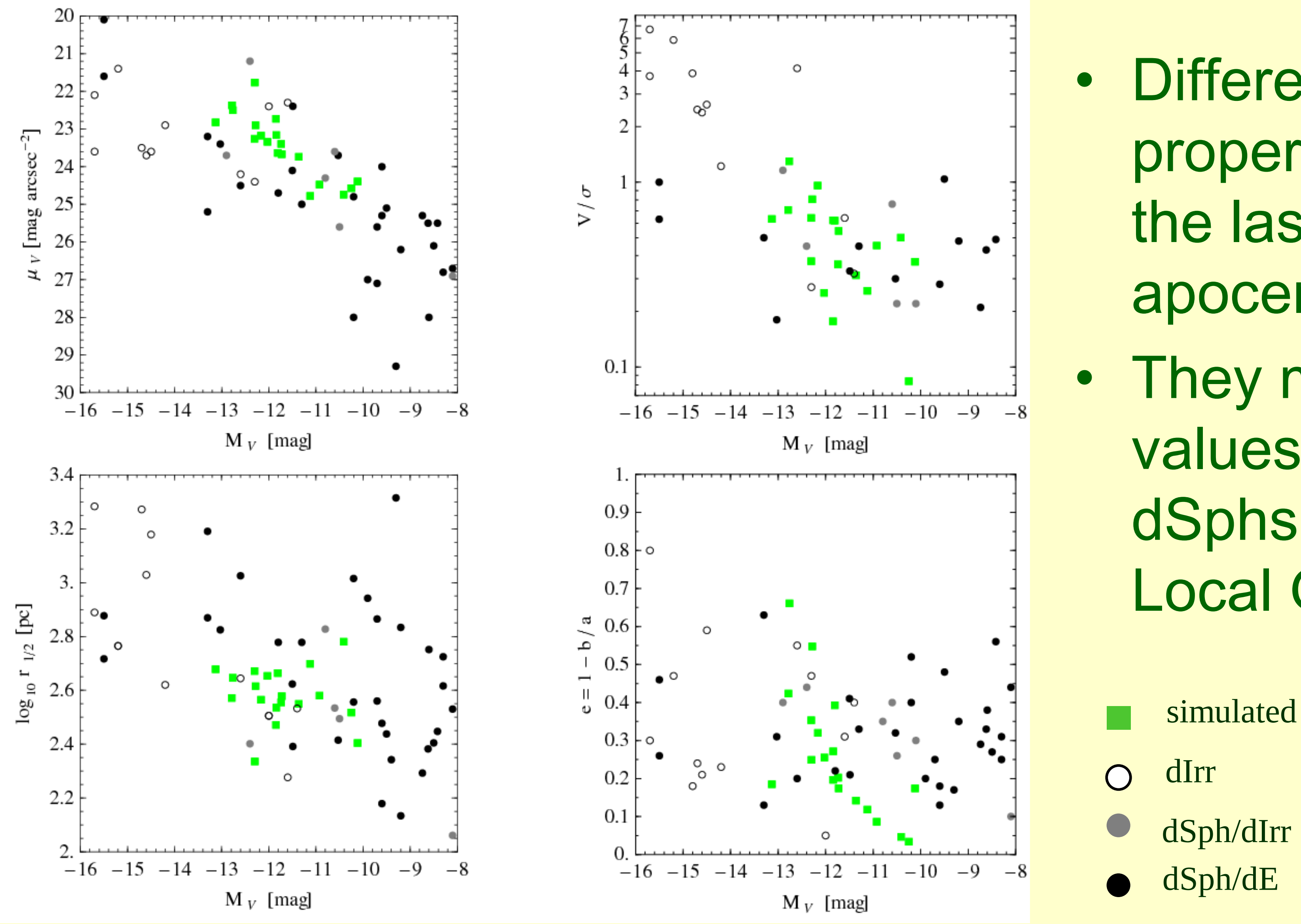


Evolutionary tracks

- Tracks in the M_V–μ_V plane move the dwarfs to fainter magnitudes and lower surface brightness
- The correlation suggests that dSph galaxies indeed formed from late-type progenitors

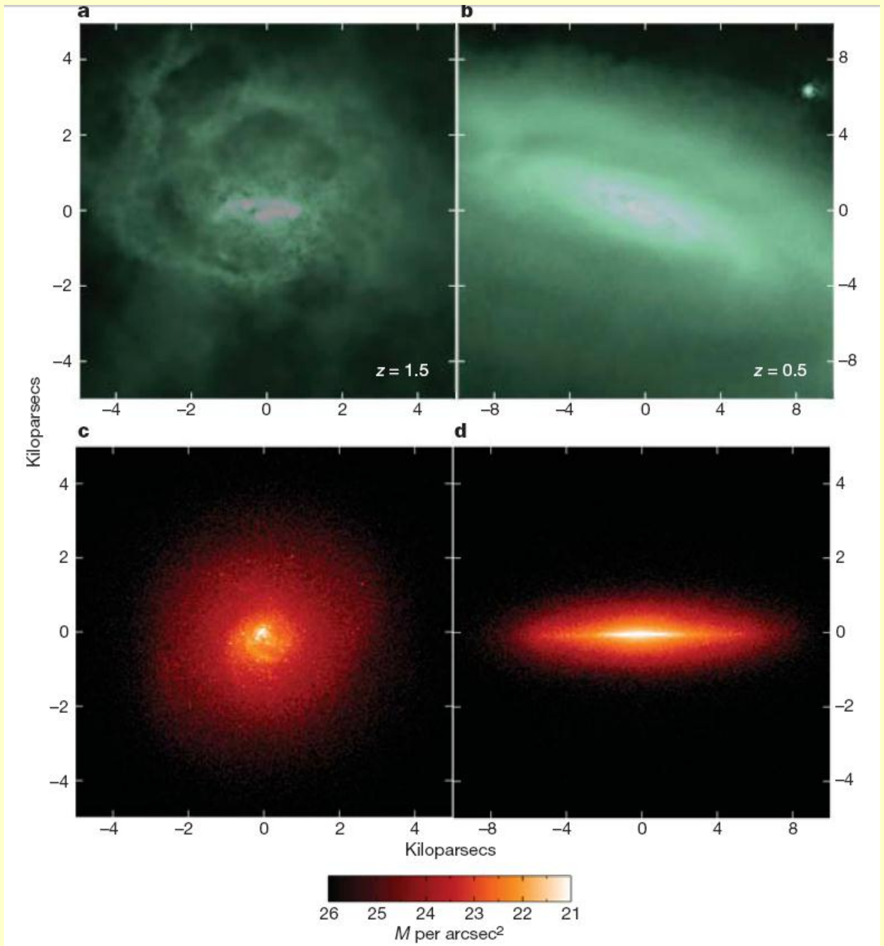
Łokas et al. 2011

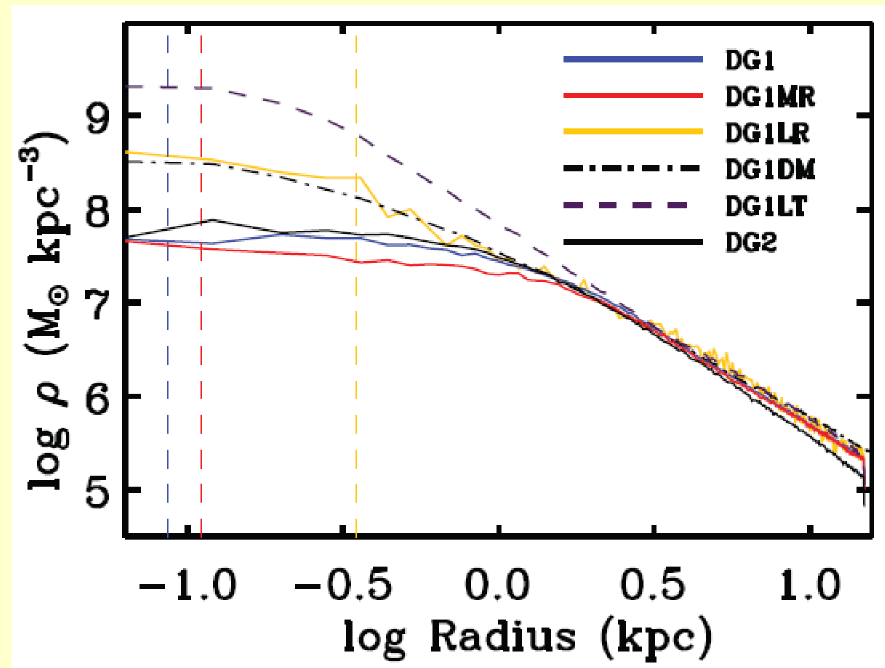
Final properties



- Different properties at the last apocenter
- They match values for dSphs in the Local Group

Shallower profiles?

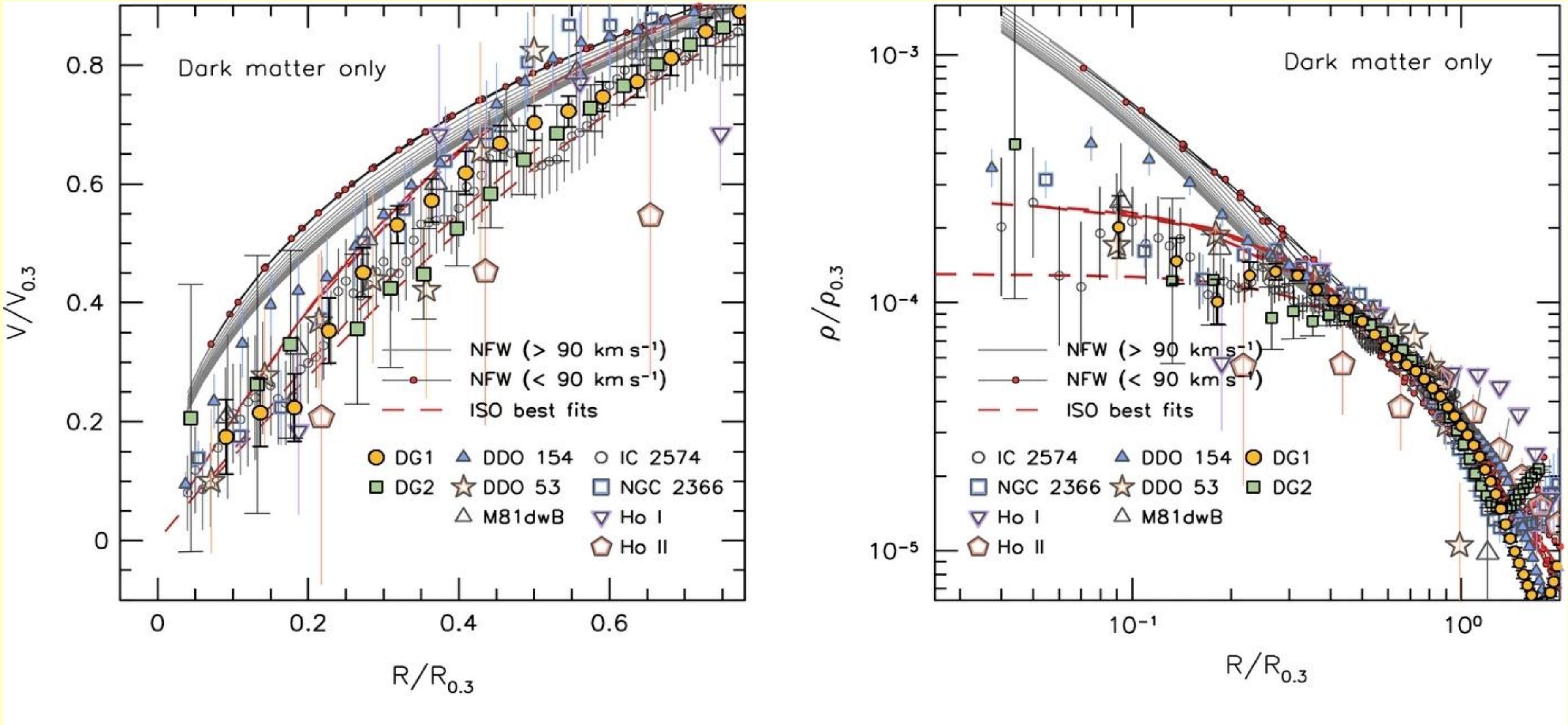




DM profiles are strongly modified by baryonic processes so our progenitors may have shallower profiles

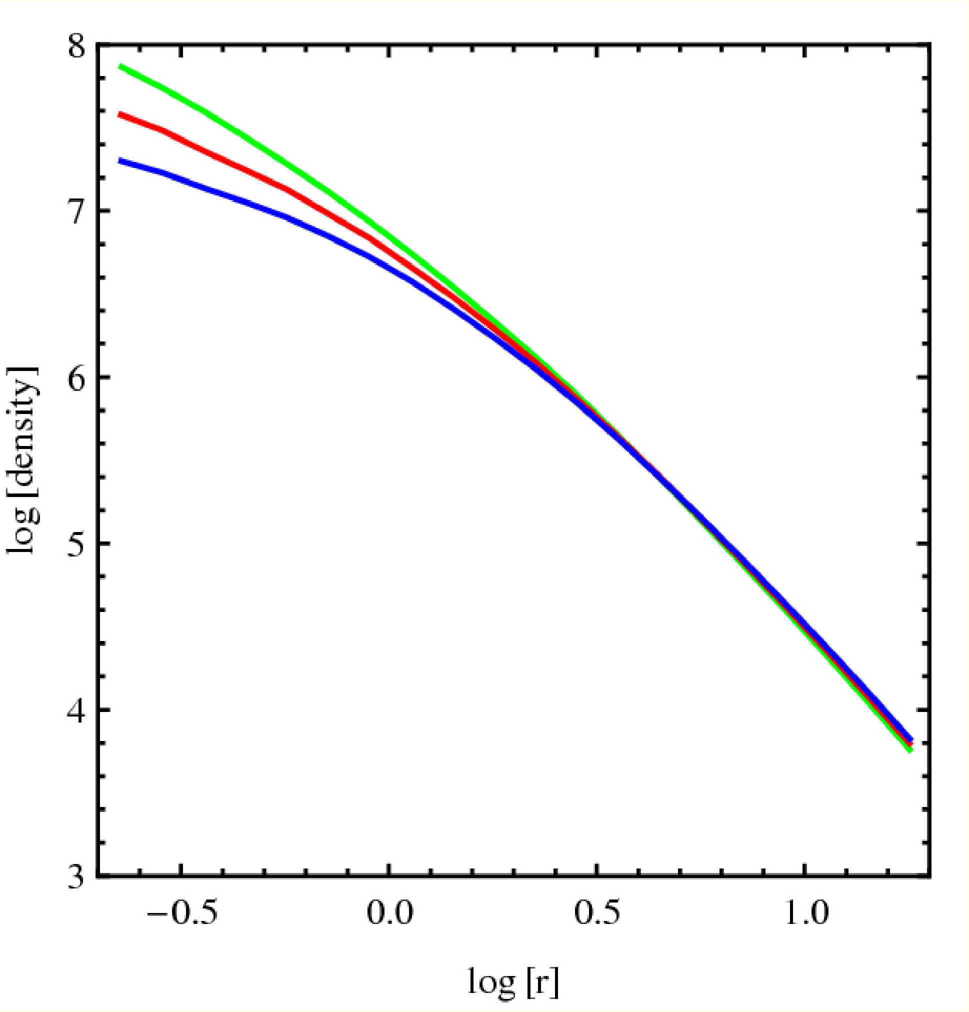
Governato et al. 2010

DM in THINGS galaxies



Oh et al. 2011

Shallower dark matter profiles



Dark matter profiles

$\rho \sim (r/r_s)^{-\alpha} (1+r/r_s)^{\alpha-3}$

with different initial inner slopes

$\alpha=1$, $\alpha=0.6$, $\alpha=0.2$

on the same orbit with typical eccentricity

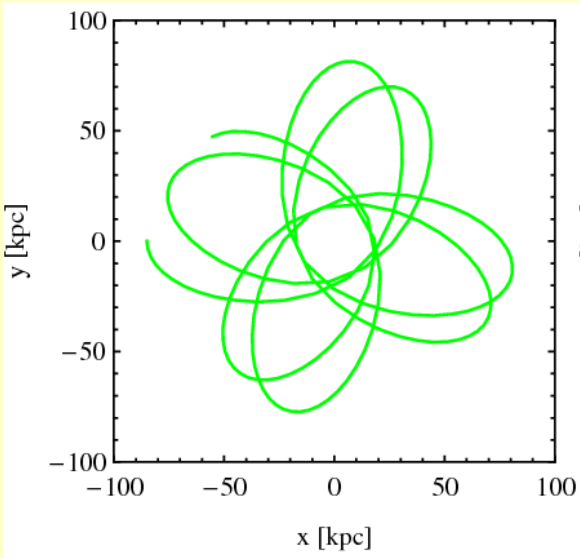
$r_{apo} / r_{peri} =$

85 kpc/17 kpc = 5

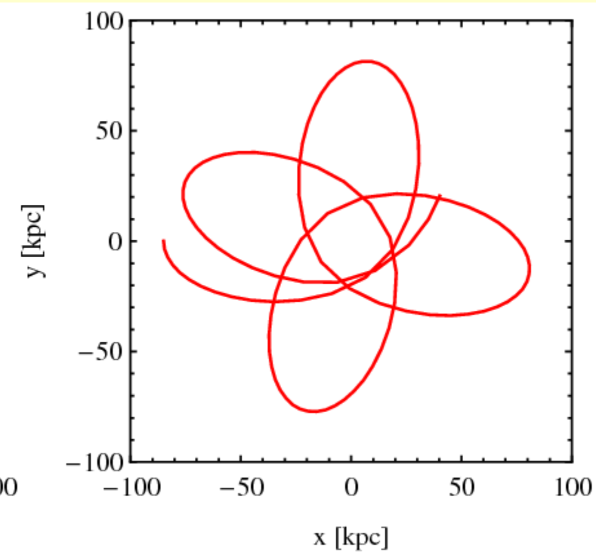
Łokas et al. 2012

Evolution with different α

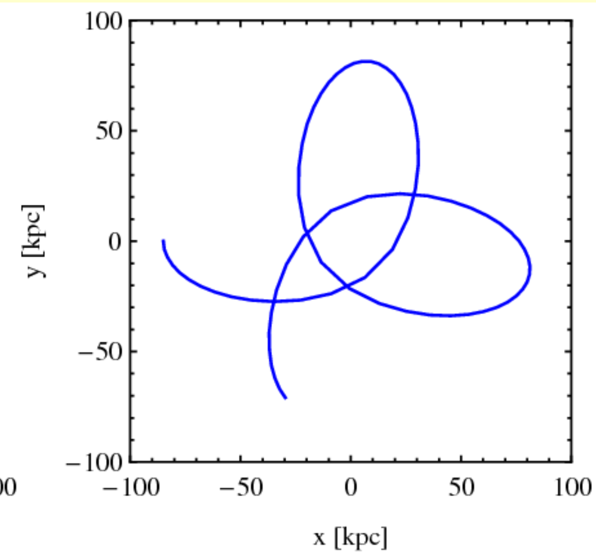
α=1



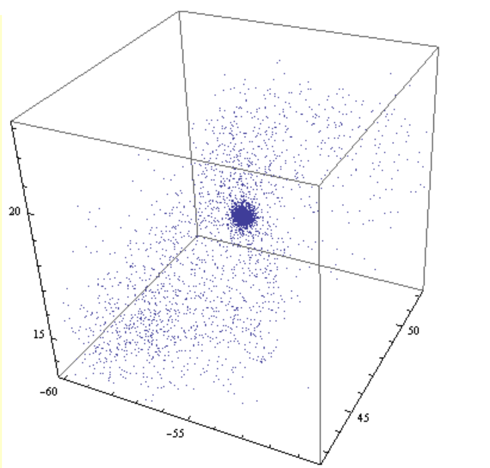
α=0.6



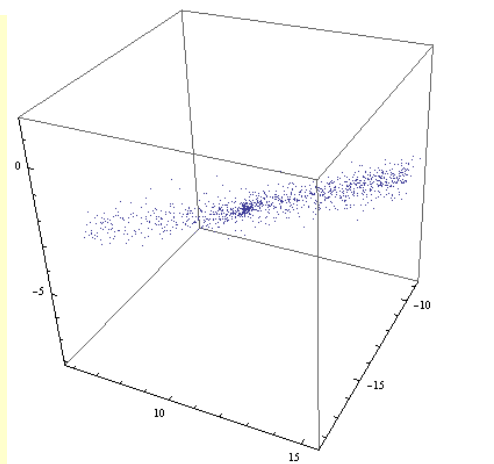
α=0.2



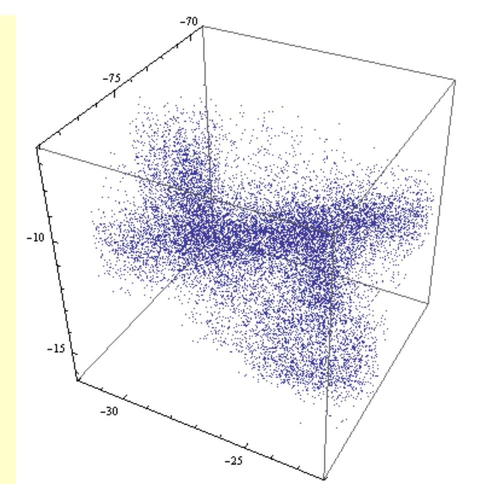
10 kpc



10 Gyr

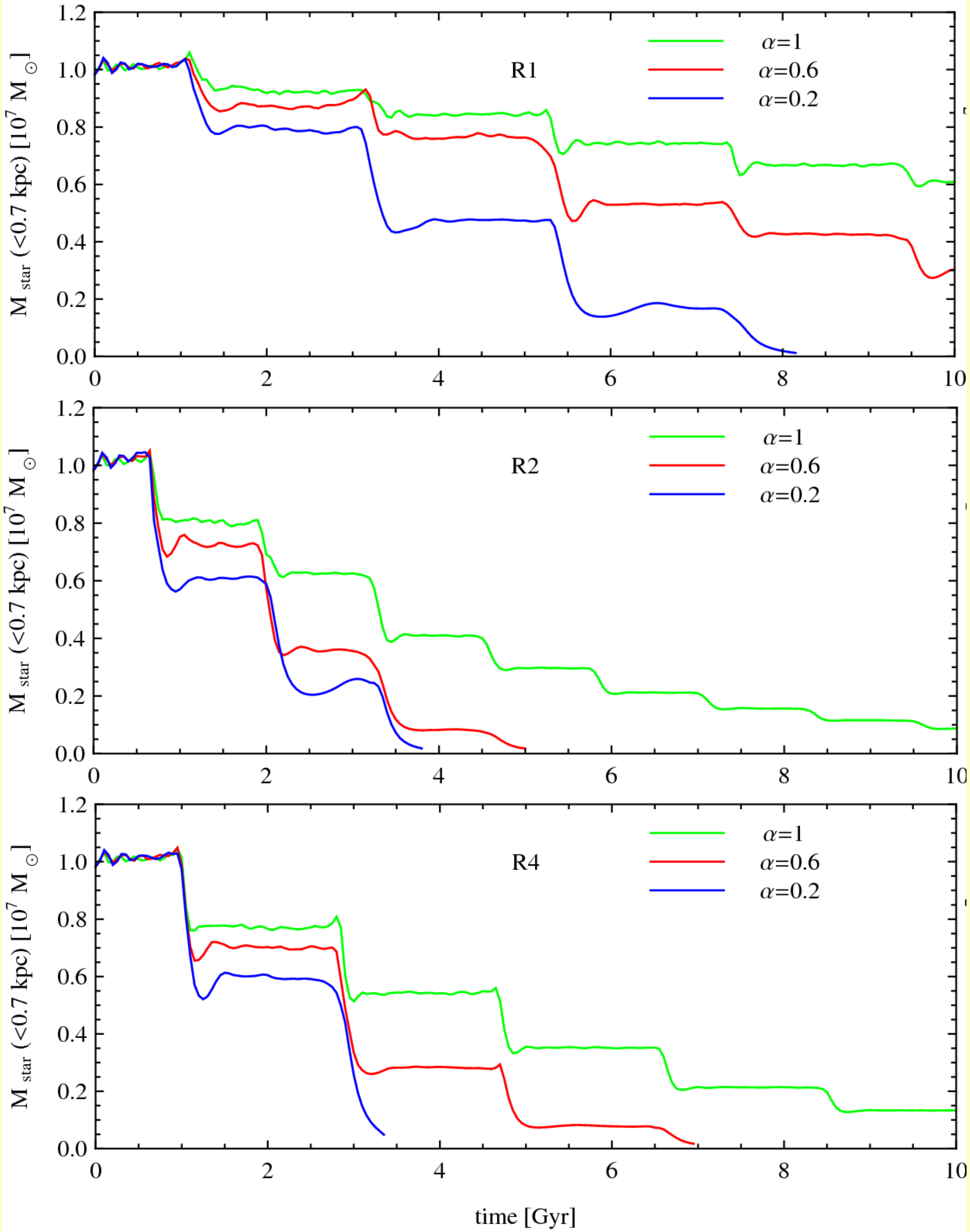


6 Gyr



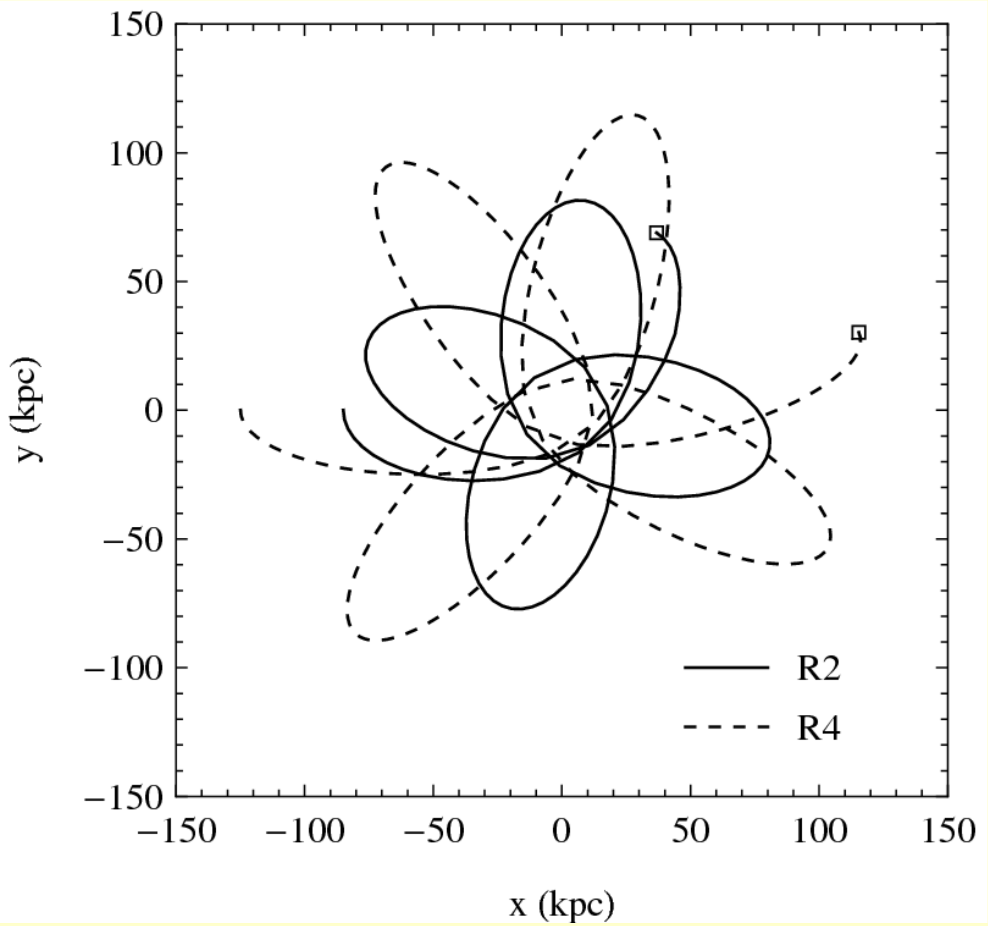
4 Gyr

Destruction of dwarfs



- Dwarfs with shallower cusps are more easily destroyed
- This must have implications for the MSP

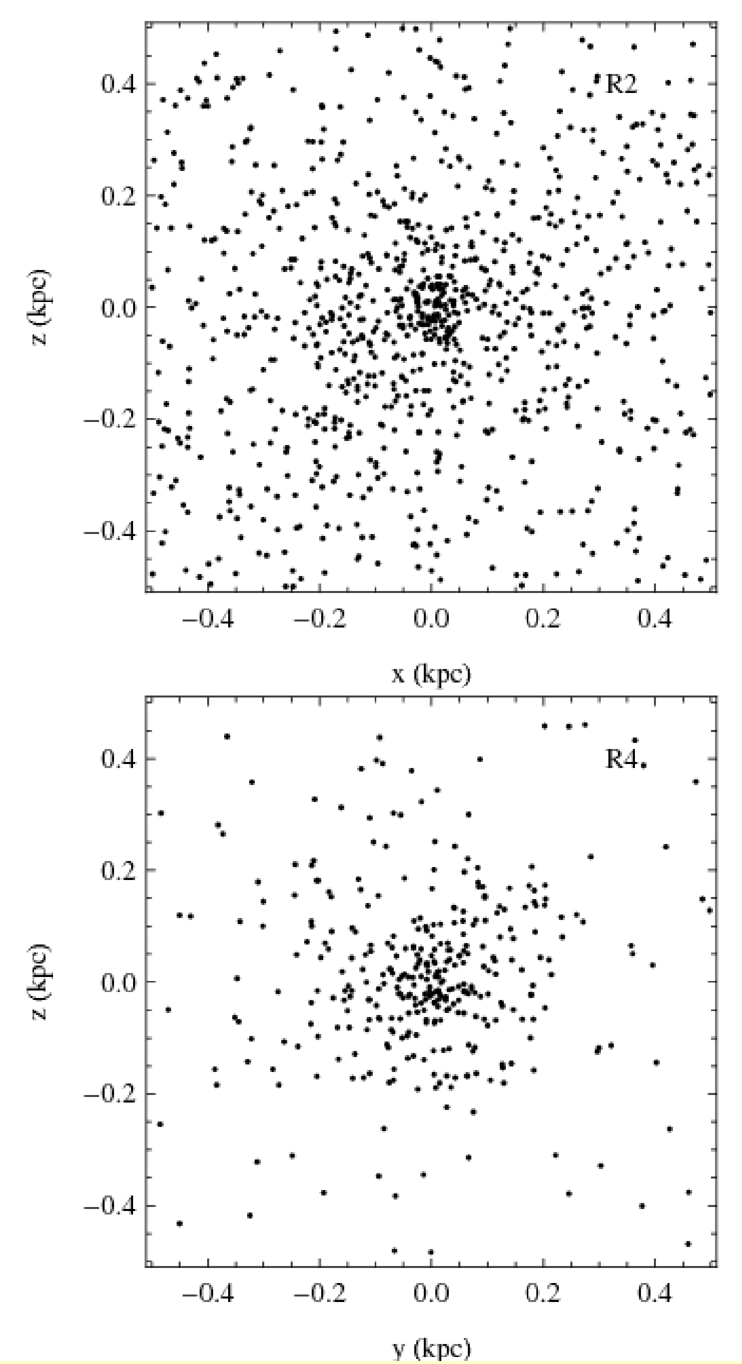
Making an ultra-faint dwarf



Ultra-faint dwarfs were produced on two relatively tight orbits R2 and R4 with α=0.6

	r_{apo} / r_{peri}
R2	85 kpc/17 kpc
R4	125 kpc/12.5 kpc

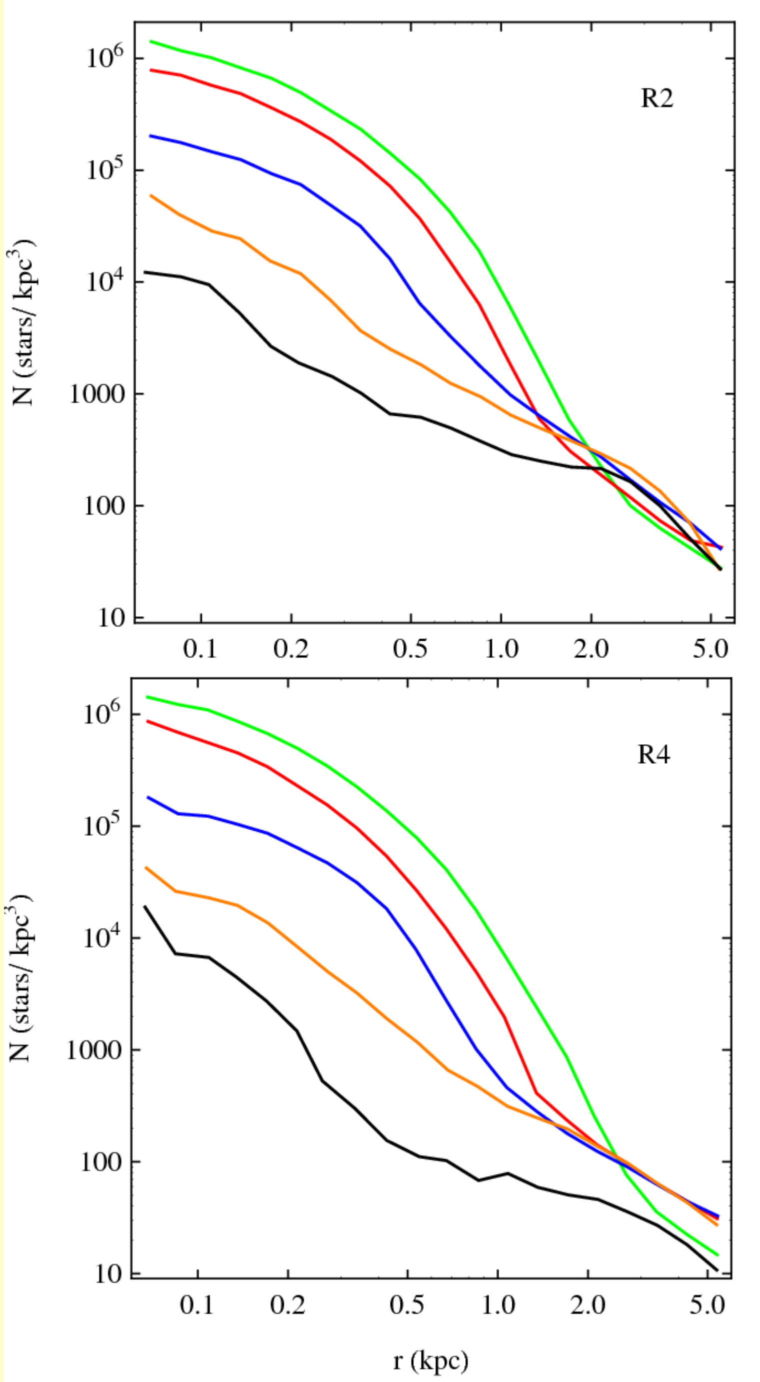
Łokas et al. 2012



Simulated UFDs

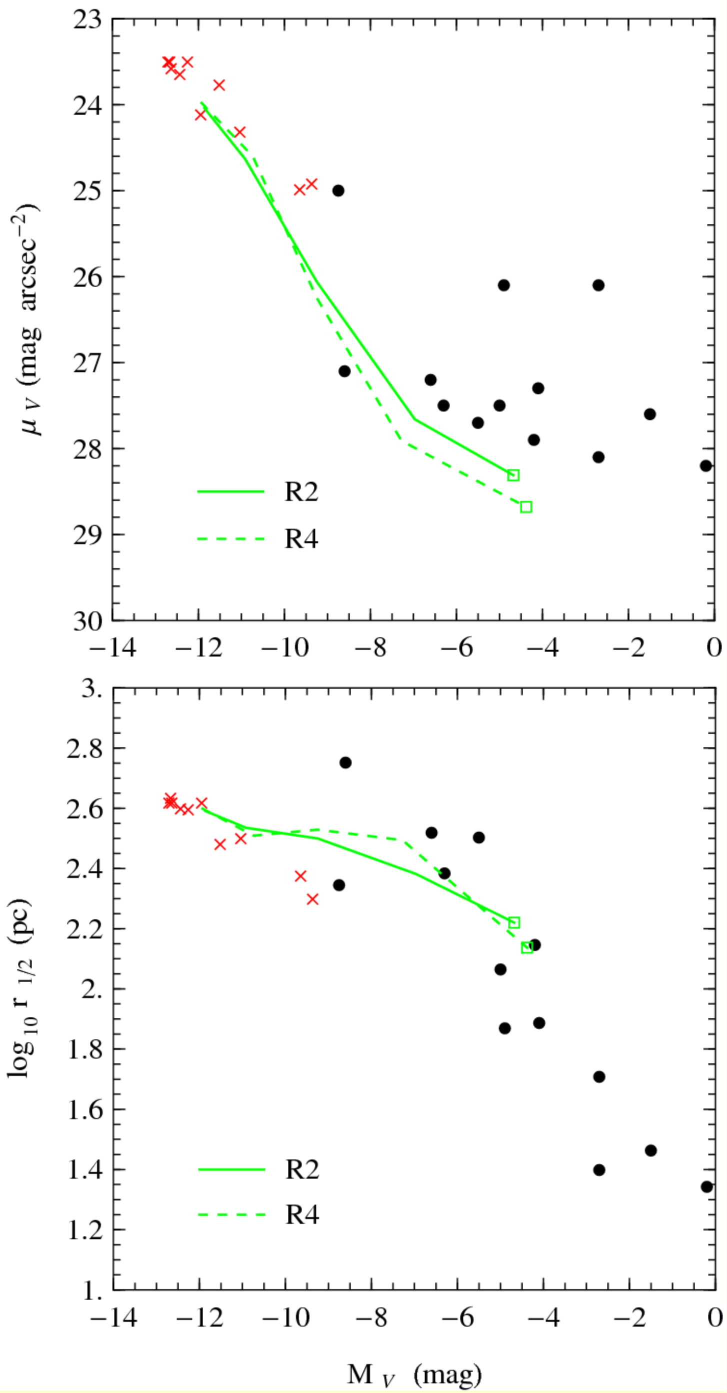
- The simulated UFDs were identified at the 6th apocenter of each orbit
- They contain only a few hundred stars in a 1 kpc cube

Density profiles of stars



- Density distributions of the stars are gradually decreased
- Both the total luminosity and the half-light radius decrease

Observational parameters



Parameter	R2	R4
$r_{\rm apo}$ (kpc)	85	125
$r_{\rm peri}$ (kpc)	17	12.5
$T_{\rm orb}$ (Gyr)	1.3	1.8
$N_{\rm apo}$	6	6
$T_{\rm la}$ (Gyr)	6.4	9.3
$L_V (10^3 L_\odot)$	6.38	4.84
M_V (mag)	−4.68	−4.38
μ_V (mag arcsec^{-2})	28.3	28.7
$r_{1/2}$ (kpc)	0.166	0.137

- ● real UFDs
- □ simulated UFDs
- x simulated brighter dwarfs

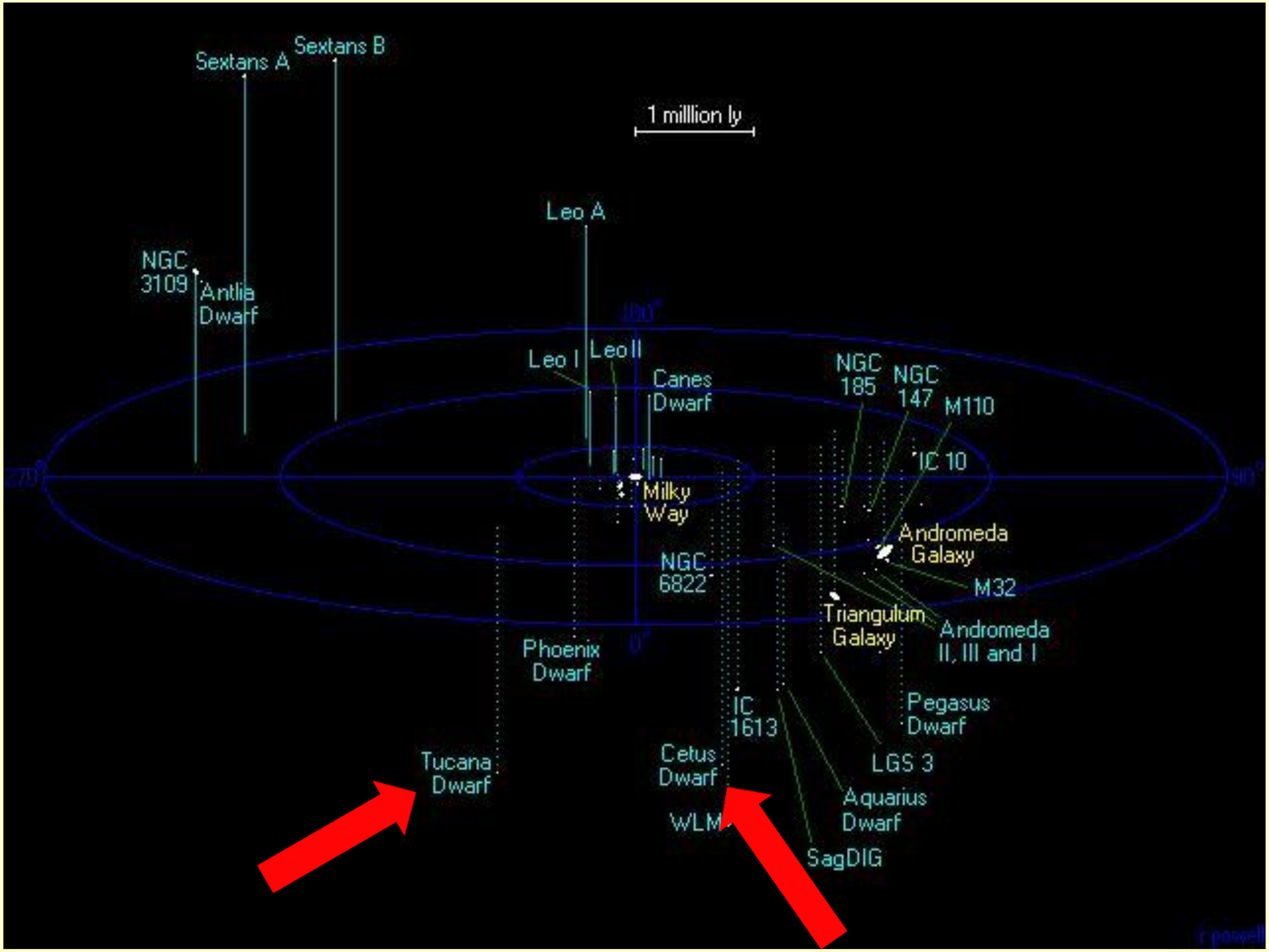
Tidal stirring works

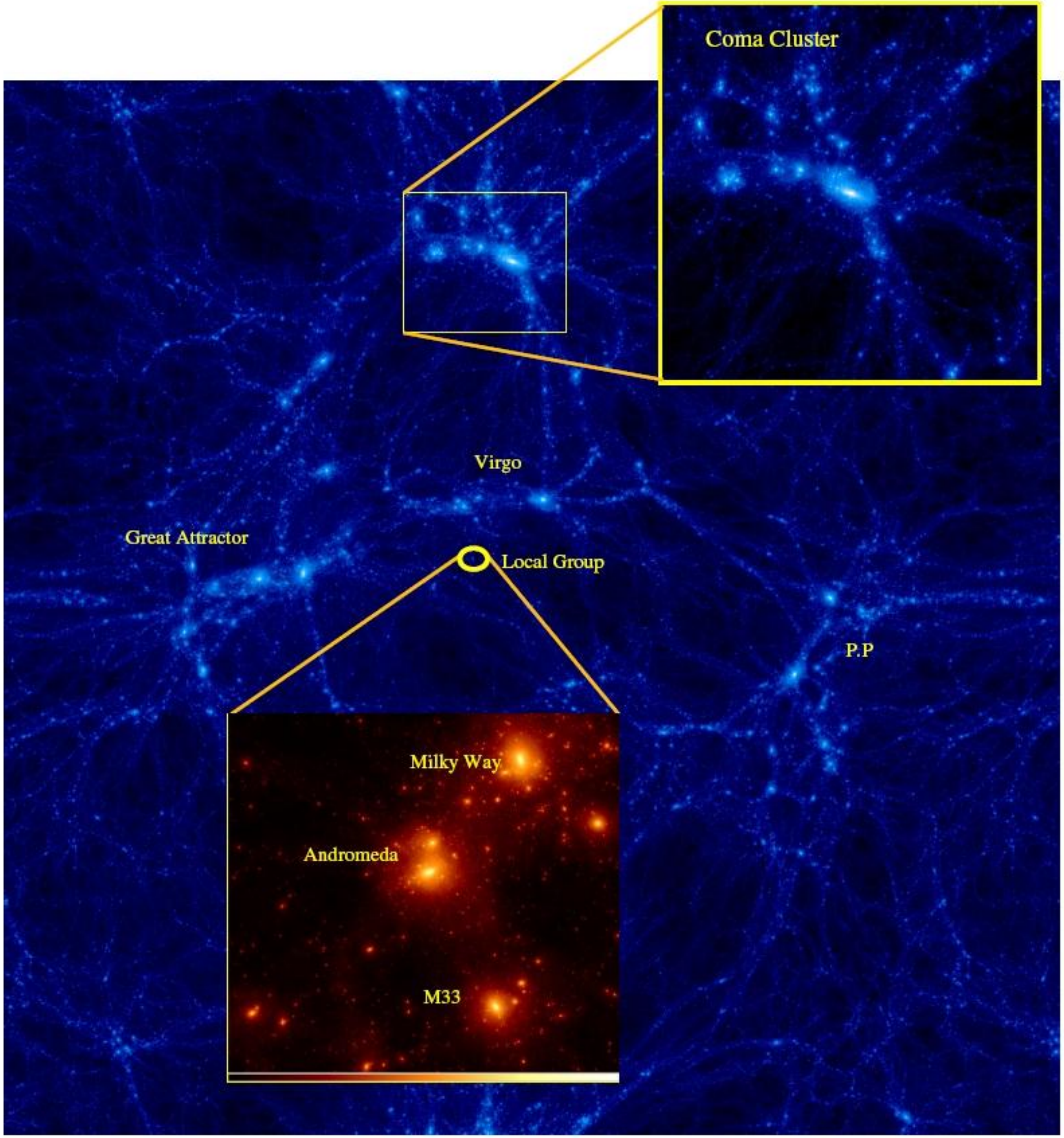
Tidal stirring is able to produce round, slowly rotating objects with properties quite similar to Local Group dSph galaxies if dwarfs evolved on orbits with pericenters smaller than ~50 kpc

However:

What about very distant dSph galaxies?

The Local Group



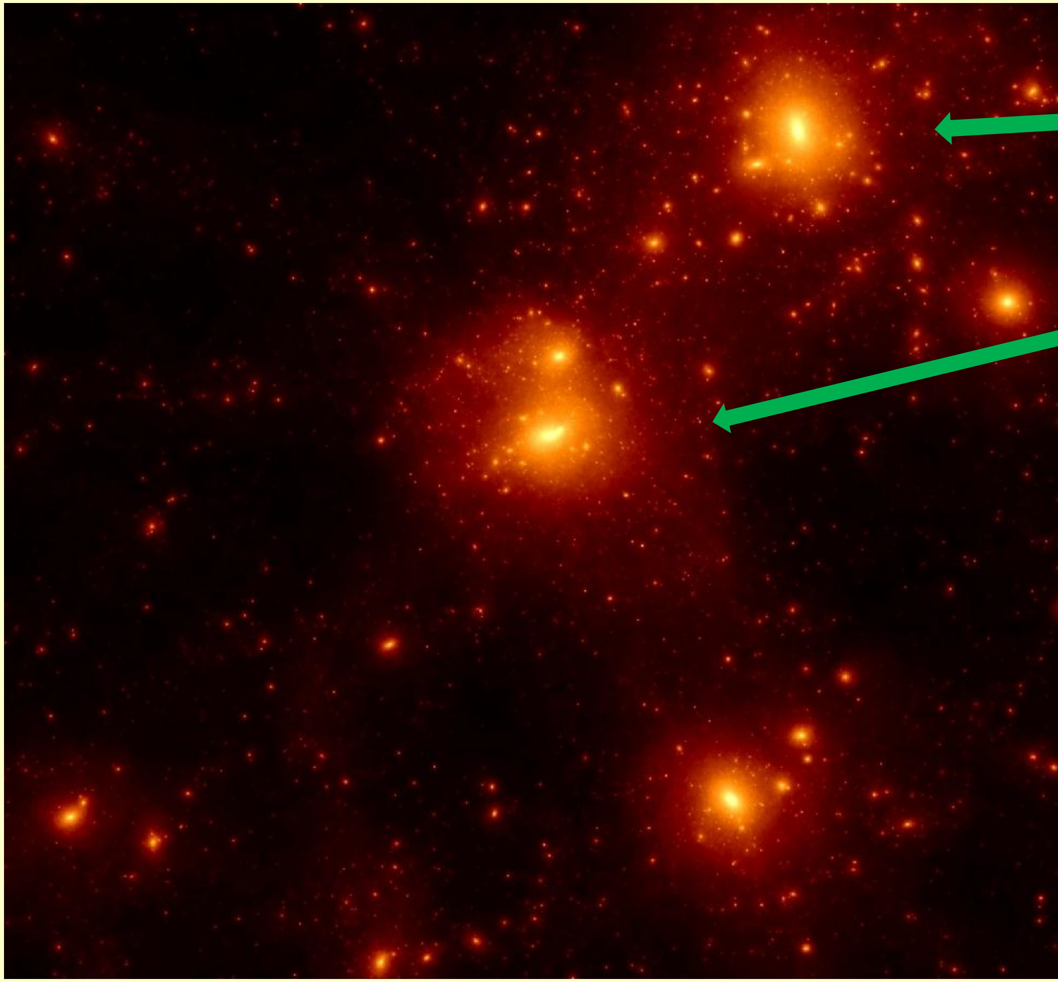


The CLUES project

Constrained simulations of the Local Universe

Box size:
160 Mpc/h

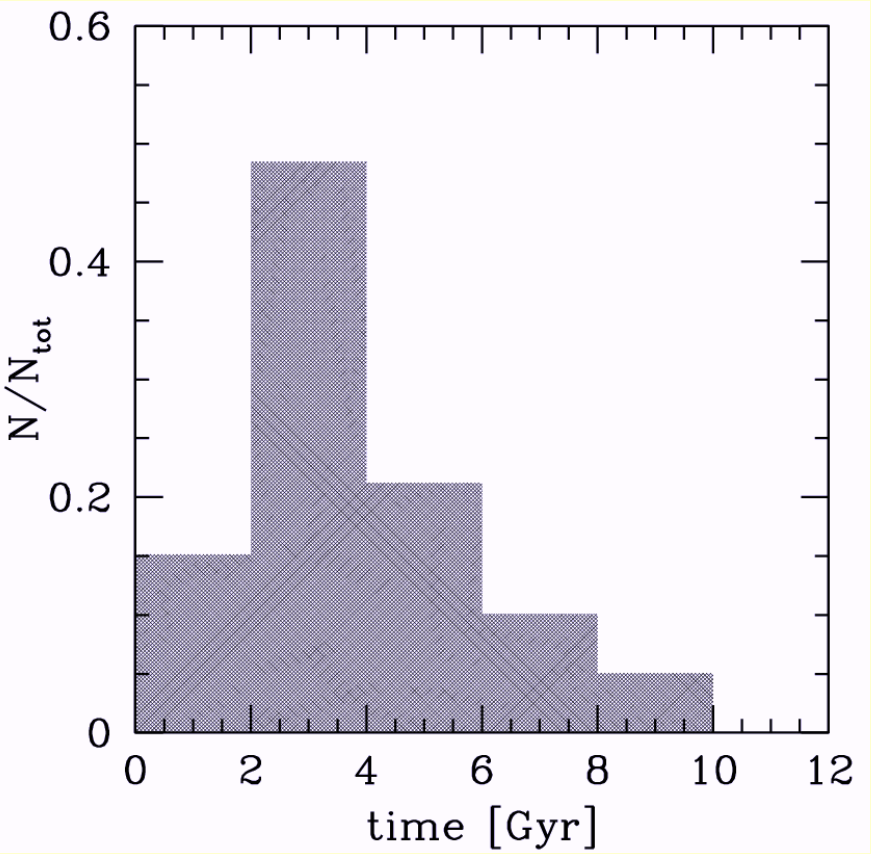
Simulation of the Local Group

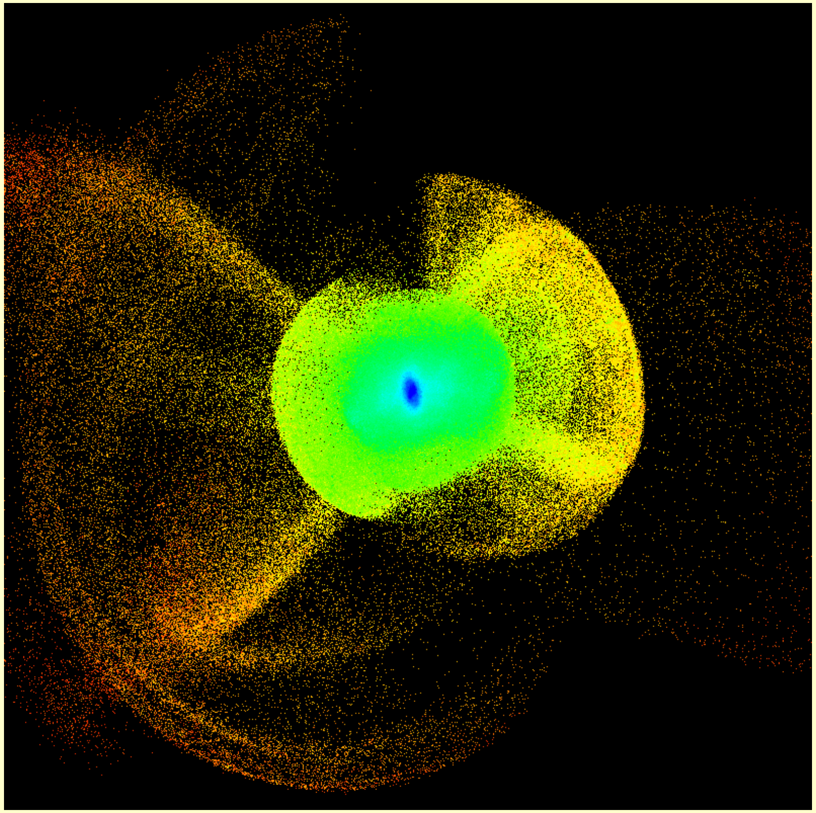


By adopting particular initial conditions we can reproduce the approximate distribution of LG members

http://www.clues-project.org/

Mergers between satellites





Klimentowski et al. 2010

Although mergers are rare, they do happen, mostly early on in the evolution, more than 7 Gyr ago.

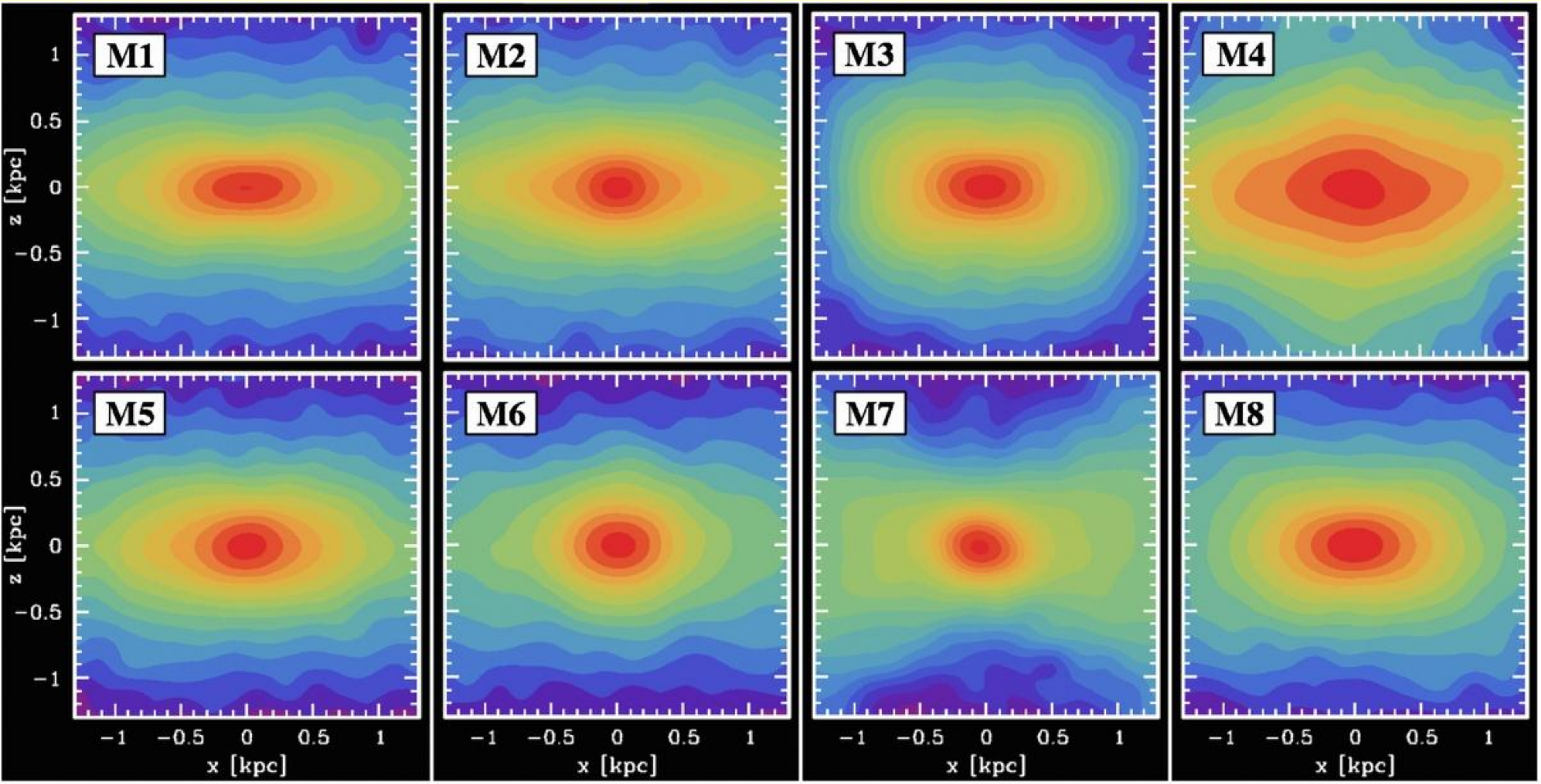
Selected merger events

Initial properties of merging dwarfs.

Merger	redshift	$M_{\rm vir}$ [$10^7 M_\odot$]	$R_{\rm vir}$ [kpc]	$V_{\rm vir}$ [km/s]	c	λ	$L_{\rm x}$	$L_{\rm y}$	$L_{\rm z}$
M1	3.02	6.51	3.15	9.43	4.48	0.046	−0.34	0.73	−0.59
		5.99	3.03	9.22	3.08	0.032	−0.21	−0.22	−0.95
M2	3.82	7.31	2.69	10.82	4.11	0.039	−0.18	−0.41	−0.89
		7.17	2.67	10.75	1.92	0.033	−0.70	0.68	0.21
M3	6.67	5.78	1.56	12.61	1.97	0.054	−0.05	−0.86	−0.50
		7.34	1.69	13.66	1.46	0.047	−0.11	−0.76	−0.64
M4	3.15	58.37	6.24	20.05	1.34	0.032	0.74	0.64	−0.20
		19.95	4.36	14.03	1.13	0.067	0.25	0.91	−0.32
M5	3.82	14.76	3.41	13.65	2.92	0.034	−0.68	0.13	−0.72
		8.21	2.79	11.26	2.61	0.065	−0.37	0.81	0.47
M6	3.82	24.96	4.04	16.30	1.67	0.051	0.80	0.21	0.56
		22.38	3.89	15.72	4.19	0.032	−0.48	0.88	0.02
M7	2.57	5.15	3.00	8.59	3.09	0.045	−0.54	−0.79	−0.31
		21.06	5.16	13.25	2.30	0.077	0.97	0.03	−0.16
M8	3.02	41.84	5.77	17.65	6.25	0.026	0.75	−0.62	−0.27
		34.18	5.39	16.52	5.88	0.031	0.99	−0.07	0.09

Kazantzidis et al. 2011

Merger products



- After 5 Gyr of evolution
- Most non-spherical appearance (view along y axis)

Properties of merger remnants

PROPERTIES OF THE SIMULATED DSPH GALAXIES FORMED BY MERGERS.

Merger	M_V (mag)	$r_{1/2}$ (kpc)	μ_V (mag arcsec^{-2})	V/σ	$e = 1 - b/a$	Color in Fig. 2
● M1	−(8.3-9.2)	0.22-0.40	25.1-27.1	0.10-0.20	0.11-0.63	green
● M2	−(8.5-9.4)	0.22-0.38	24.9-26.6	0.09-0.69	0.04-0.59	red
● M3	−(8.4-9.3)	0.24-0.32	25.0-26.7	0.12-0.70	0.14-0.45	blue
● M4	−(10.3-11.2)	1.24-1.50	26.4-27.6	0.19-1.88	0.12-0.50	black
● M5	−(9.0-9.9)	0.30-0.52	25.1-26.8	0.20-0.60	0.03-0.59	orange
● M6	−(9.7-10.7)	0.42-0.60	24.7-26.1	0.22-0.75	0.06-0.50	magenta
● M7	−(9.1-10.0)	0.28-0.38	24.4-25.9	0.33-0.92	0.08-0.54	cyan
● M8	−(10.3-11.2)	0.29-0.41	23.7-25.3	0.09-0.50	0.07-0.47	brown

● dSph (green)

● dSph? (orange)

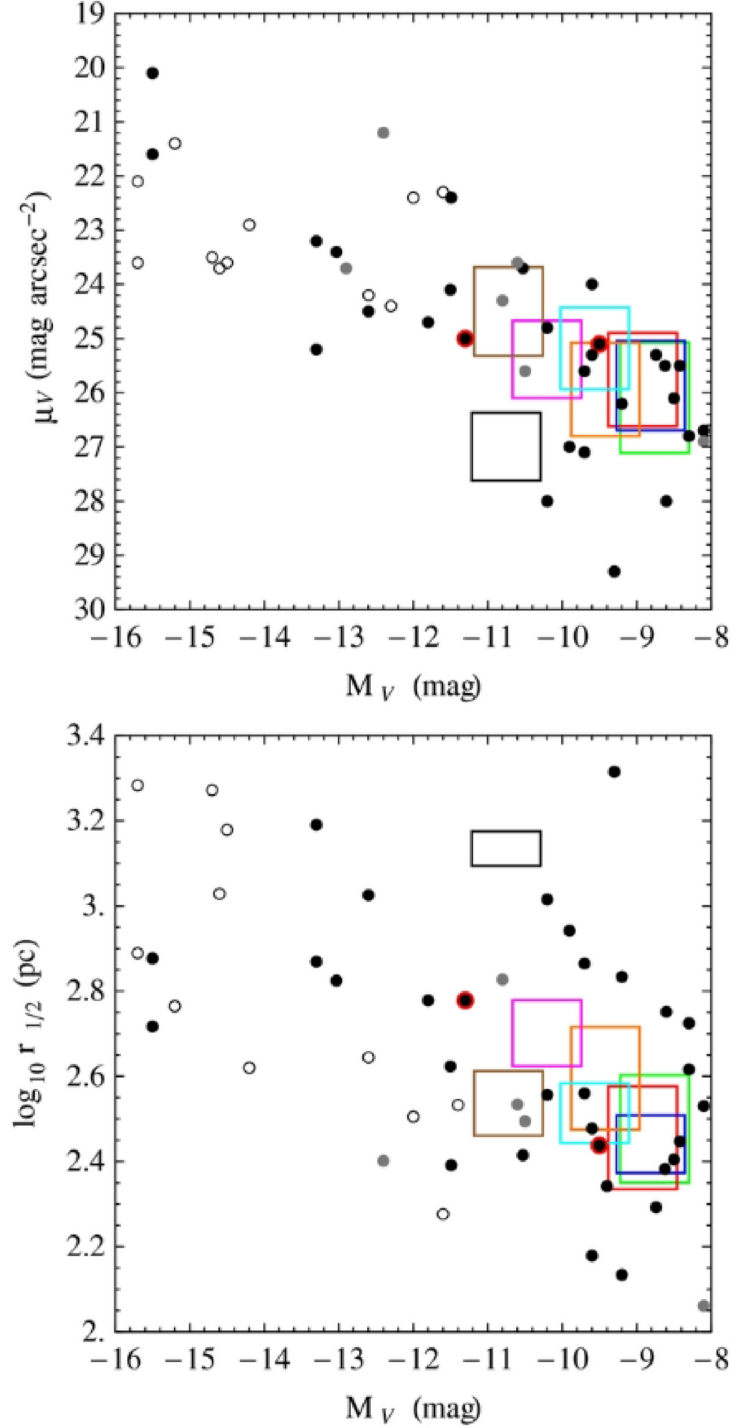
● non-dSph (red)

- Ellipticities measured at 2 $r_{1/2}$
- V is the maximum velocity on 2D map
- σ is the central velocity dispersion
- μ_V is measured within 0.2 $r_{1/2}$

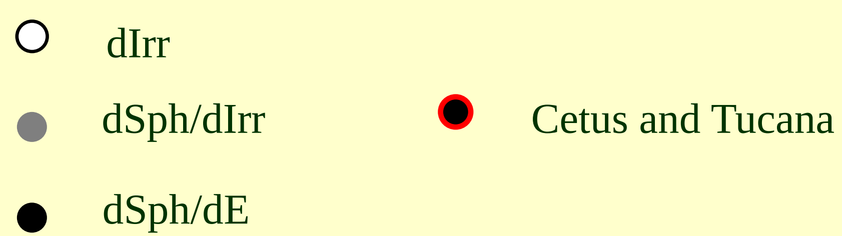
Why these results?

- Mergers are very effective in producing dSph galaxies
- Main factors: mass ratio and spin alignment
- The only clear non-dSph case M4 ($V/\sigma>1$) is produced when the mass difference of progenitors is 1:3 and spins are aligned
- The second largest $V/\sigma=0.9$ occurs for M7 with mass ratio 1:4 but spins misaligned
- Equal-mass mergers produce dSphs even if spins are aligned

Comparison with observations



Coloured rectangles indicate possible ranges of parameters of the simulated dwarfs following from different lines of sight (different $r_{1/2}$) and uncertainty in the stellar M/L

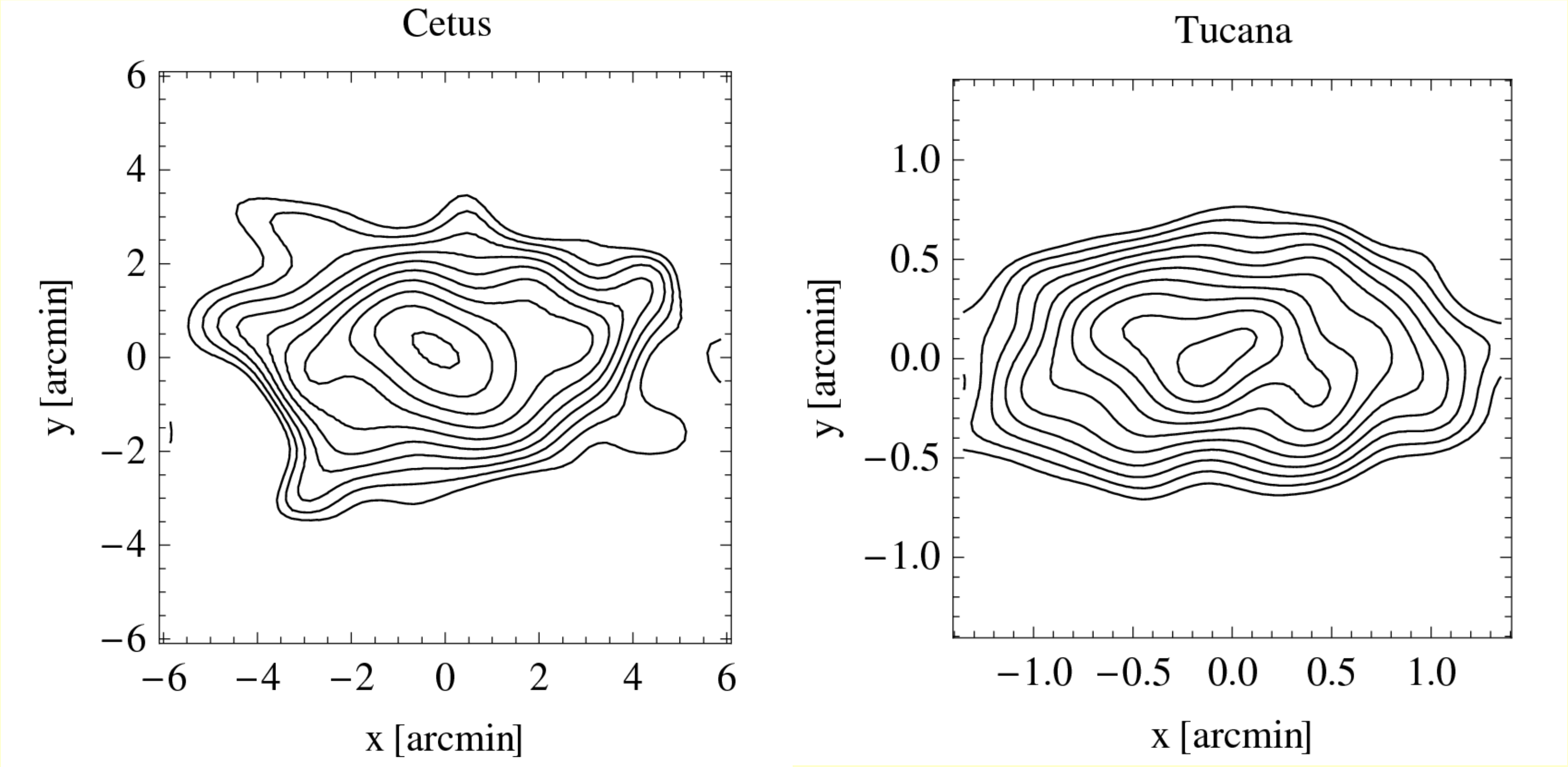


Comparison with Cetus and Tucana

PROPERTIES OF THE SIMULATED DSPH GALAXIES FORMED BY MERGERS.

Merger	M_V (mag)	$r_{1/2}$ (kpc)	μ_V (mag arcsec^{-2})	V/σ	$e = 1 - b/a$	Color in Fig. 2
M1	−(8.3-9.2)	0.22-0.40	25.1-27.1	0.10-0.20	0.11-0.63	green
M2	−(8.5-9.4)	0.22-0.38	24.9-26.6	0.09-0.69	0.04-0.59	red
M3	−(8.4-9.3)	0.24-0.32	25.0-26.7	0.12-0.70	0.14-0.45	blue
M4	−(10.3-11.2)	1.24-1.50	26.4-27.6	0.19-1.88	0.12-0.50	black
M5	−(9.0-9.9)	0.30-0.52	25.1-26.8	0.20-0.60	0.03-0.59	orange
M6	−(9.7-10.7)	0.42-0.60	24.7-26.1	0.22-0.75	0.06-0.50	magenta
M7	−(9.1-10.0)	0.28-0.38	24.4-25.9	0.33-0.92	0.08-0.54	cyan
M8	−(10.3-11.2)	0.29-0.41	23.7-25.3	0.09-0.50	0.07-0.47	brown
Cetus	−11.3	0.600	25.0	0.45	0.33	
Tucana	−9.5	0.274	25.1	1.04	0.48	

Shapes of Cetus and Tucana



Where do they end up?

- We traced the history of the merger remnants in the LG simulation until z=0
- Four out of seven dSph candidates (M2, M3, M6, M7) survived in isolation at outskirts of the Local Group at ~1 Mpc from MW or M31 (Cetus and Tucana)
- Three merger remnants ended up as subhaloes of bigger systems, M1 as close as 80 kpc from M31 (Fornax?)

Conclusions

- Tidal stirring is able to reproduce the basic observational properties of dSph galaxies in the Local Group if their orbits are tight enough
- Shallower initial dark matter profiles lead to the formation of ultra-faint dwarfs and easier destruction
- Distant dSph galaxies could be produced by mergers
- Final products of both processes show remarkable similarities and the features that could distinguish between them are hard to identify